Remote Sensing of Mangrove Wetlands: Relating Canopy Spectra to Site-Specific Data

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Abstract
Remote sensing was examined as a tool to describe the spectral and structural changes within and between mangrove species and community types. To accomplish this goal, high-resolution canopy reflectance spectra were obtained at 21 mangrove sites in southwest Florida. This was in addition to leaf spectra, canopy closure, height, and species composition from a number of these sites. High relative variability typified measurements of canopy reflectance spectra, canopy height, and percent species composition, while leaf reflectance variances within species (black or red, about 0.04 to 0.06 percent) were higher than between species (about 0.02 percent). A transformed canopy closure variable — Leaf Area Index (LAI) — was low with little variance, and it was significantly correlated to canopy height but not to species composition. Mean reflectances were generated for the blue, green, red, and near-infrared (NIR) wavelength regions from the obtained canopy reflectance spectra by using either user-defined bandwidths or bandwidths defined for the Advanced Very High Resolution Radiometer, Thematic Mapper, and XMS (SPOT) sensors. Results from these sets of reflectances in combination with correlation analyses suggest blue and red reflectances were redundant as were SPOT panchromatic and green reflectances and all normalized difference vegetation indexes derived for each set of NIR and red reflectances. Eighty-four percent of the LAI variance was explained by using any generated normalized difference vegetation index; however, species composition was not correlated to any combination of reflectance bands or vegetation index.

Introduction
Mangrove wetlands dominate approximately 75 percent of the world's tropical and subtropical coastlines between 25°N and 25°S latitude (Heald and Odum, 1975), and are among the world's most productive ecosystems (Eitel, 1972; Odum *et al.*, 1982; Mitsch and Gosselink, 1993). In terms of net primary production, healthy mangroves are deemed the most productive, followed by sea grasses, marsh grasses, other coastal ecosystems (Odum *et al.*, 1982), and then by all other ecosystems combined (Eitel, 1972; Mitsch and Gosselink, 1986). Globally, mangrove detritus supports the highest productivity of associated estuarine and coastal ocean waters (Saenger *et al.*, 1983) while, within areas of the Gulf of Mexico, most commercial and sport finfish are linked to food chains originating from mangrove detritus (Lugo and Snedaker, 1974; Heald and Odum, 1975).

Conservation of mangrove wetlands is urgently needed; the continued viability of these ecosystems depends on managing them in a sustainable fashion (Saenger *et al.*, 1983). Managers must formulate practices that consider the functions and values (amenities provided from within the wetland system and beyond its boundaries) of these wetlands. In a majority of mangrove wetlands, however, the plant types and the distribution and extent of plant communities are poorly known (Tomlinson, 1986). Further, little information exists on the structural aspects of mangroves (Odum *et al.*, 1982; Saenger *et al.*, 1983). This lack of information is unfortunate because quantitative data on structure would be useful in environmental surveys and impact statements. It would also be potentially useful for understanding basic processes such as succession and primary production (Odum *et al.*, 1982).

To understand the structure and function of mangrove ecosystems in a holistic context, a regional assessment of the physical and biological characteristics is required (Lulla and Mausel, 1983). Remote sensing is the only technique that can be used to measure these characteristics over large areas (Botkin *et al.*, 1984) and that can provide these data on a repetitive basis (Lulla and Mausel, 1983).

In remote sensing studies using photographic sensors, the leaf optical signature and canopy structure are used to classify mangrove communities and identify changes (Patterson, 1986; Terchunian *et al.*, 1986). Patterson (1986) surmised that high near-infrared (NIR) reflectance associated with pure stands of red mangroves was due to the canopies' dense crowns, high stand density, flattened leaves, and high leaf reflectance. Low NIR reflectance associated with pure stands of black mangroves was deemed to be due to the canopies' sparse crowns, lower stand density, smaller leaves, and lower leaf reflectance. Patterson further concluded that the variability in canopy reflectance signature associated with mixed (red and black) mangrove communities was related to the relative proportion of each species comprising the community.

Studies have used digital remote sensing techniques to examine mangrove wetlands (e.g., Bina *et al.*, 1978; Lorenzo *et al.*, 1979; Untawale *et al.*, 1980; Butera, 1983; Hardisky *et al.*, 1986; Dutrieux *et al.*, 1990; Jensen *et al.*, 1991; Blasco *et al.*, 1992). None of these, however, have explicitly related

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Photogrammetric Engineering & Remote Sensing,
Vol. 62, No. 8, August 1996, pp. 939–948.

0099-1112/96/6208–939$3.00/0

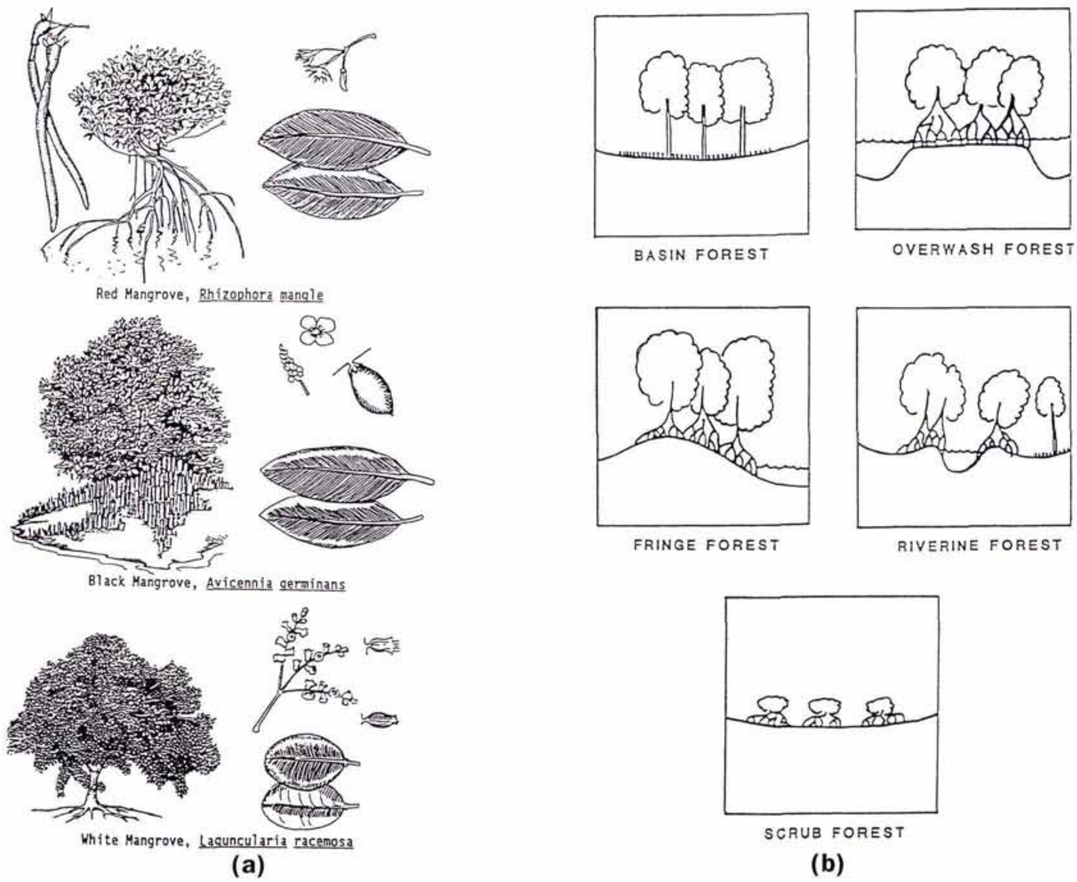

Figure 1. Mangrove species (a) and community types (b) present within the study area (adapted from Odum *et al.* ((1982)).

spectral variability to canopy structure and species composition, nor to community type. Jensen *et al.* (1991) did relate canopy leaf area index (LAI) to a vegetation index generated from the SPOT XMS sensor.

Objective

The objective of this study was to examine the following questions:

- What are the spectral and structural changes within and between mangrove species and community types?
- What are the relationships between the canopy spectral variability at the blue, green, red, and NIR wavelength regions and canopy species composition and structural variability?

Bandwidths associated with these wavelength regions were either defined in the study or simulated for the Thematic Mapper (TM), SPOT XMS and Panchromatic, and Advanced Very High Resolution Radiometer (AVHRR) satellite sensors.

To accomplish the objective, site-specific field measurements and high-resolution spectral data of mangrove communities were collected and analyzed. First, field measurements and estimates of canopy closure, height, percent species composition, and leaf and canopy reflectances were obtained. Second, the spectral data and transforms of these data were compared to field measurements of stand characteristics by using univariate statistics, simple correlation, and regression techniques. Finally, the comparisons are discussed in terms of delineating different mangrove species and communities, and predicting canopy leaf area index (LAI).

Mangroves

Mangroves encompass 12 families and over 50 species (Mitsch and Gosselink, 1993). Old world mangroves make up a majority of these species and particularly dominate the Indonesia and West Pacific region (Davies, 1973; Mitsch and Gosselink, 1993). New world mangroves are found on the west coast of Africa and the Americas and comprise four species (red mangrove [*Rhizophora mangle L.*], black mangrove [*Avicennia germinans L.*], white mangrove [*Laguncularia racemosa*], and, though not strictly a mangrove, buttonwood [*Conocarpus erectus*]; Davies, 1973; Mitsch and Gosselink, 1993)(Figure 1a). In southwest Florida, the four species occur in monospecific stands and in varying mixtures that can be generalized into the five following community types linked to local tidal dynamics and terrestrial surface drainage (Lugo and Snedaker, 1974; Twilley *et al.*, 1986) (Figure 1b):

BASIN – These are inland depressions that channel terrestrial runoff toward the coast. The more coastal positions are influenced by daily tides and dominated by red mangroves, while the more inland areas, less frequently tidally influenced, are monospecific or any mixture of red, black, or white mangroves (Mitsch and Gosselink, 1993; Twilley *et al.*, 1986);
OVERWASH – A small island or spit that is flushed daily at high tide and dominated by red mangroves (Lugo and Snedaker, 1974; Mitsch and Gosselink, 1993);
FRINGE – Red mangroves dominate these areas that are inundated daily and occur along waterways and protected shorelines whose elevations are higher than mean high tide (Lugo and Snedaker, 1974; Mitsch and Gosselink, 1993);
RIVERINE – Red mangroves usually dominate these brackish areas (Teas, 1980) that are confined to narrow strips along tidal rivers that experience daily terrestrial runoff and tidal flushing (Odum *et al.*, 1982; Twilley *et al.*, 1986); and
SCRUB – This community can include any or all species where growth is probably nutrient-limited. These stands are usually

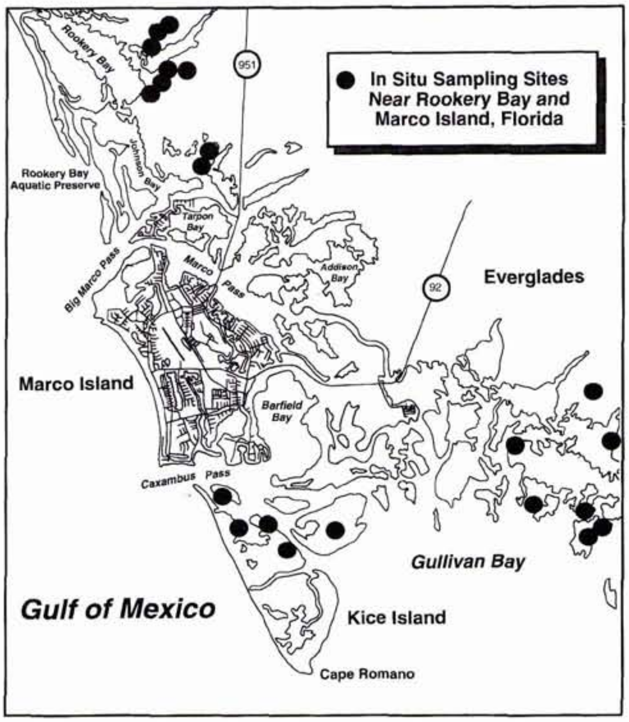

Figure 2. Mangrove areas in the southwest Florida coast that include the northwest Everglades, the Ten Thousand Islands, and the Rookery Bay Reserve areas. Four species of mangroves occur here: red mangrove (*Rhizophora mangle L.*); black mangrove (*Avicennia germinal L.*); white mangrove (*Laguncularia racemosa*); and, though not strictly a mangrove, buttonwood (*Conocarpus erectus*) (Mitsch and Gosselink, 1986; Davies, 1973). Field-site locations are indicated.

less than 1.5 m, but often greater than 40 years old (Odum *et al.*, 1982).

Mangrove Stand Structure and Biomass

Differences exist in biomass among mangrove community types depending on stand age, stand history, and stand structural difference (Lugo and Snedaker, 1974). Generally, 90 percent of the leaf biomass exists in the upper 4 m of the canopy; this layer also intercepts 95 percent of the available light (Teas, 1980; Odum *et al.*, 1982). This restricted canopy depth, in association with continuous year-round leaf fall (related to the shade intolerance of the canopy leaves), may suggest a tendency for the canopy depth to remain constant despite an increase in the canopy height (Odum *et al.*, 1982).

Mangrove Leaf Area Index—LAI

Mangrove LAIs are low compared to tropical forests where LAIs range from about 10 to 20 (Odum *et al.*, 1982). Single measurements of LAI within Puerto Rico and southwest Florida red mangrove wetlands were 4.4 and 3.5, respectively (Odum *et al.*, 1982). An LAI observed within a black mangrove wetland in Florida was 5.1 but, in a different study, LAIs associated with Florida black mangroves ranged from 1.0 to 4.0 with an average of 2.0 to 2.5 (Odum *et al.*, 1982). The low LAIs may result from (1) the very effective light interception by the canopy, (2) the inability of lower canopy leaves to flourish at low light intensities, and (3) the absence of a low-light adapted plant layer on the mangrove forest floor. Models predict the maximum photosynthesis of red mangroves to occur at an LAI of 2.5 (Odum *et al.*, 1982).

The Study Area

In the United States, mangroves grow along the Atlantic and Gulf coasts of Florida south of 28° to 29°N latitude (Odum *et al.*, 1982). South Florida mangroves dominate 2,172 km of coastline (Haddad and Harris, 1985) and cover 162,000 to 219,000 ha in area (Odum *et al.*, 1982). Mangroves are best developed in the southwest Florida coast that includes the northwest Everglades, the Ten Thousand Islands, and the Rookery Bay Reserve areas (Figure 2).

This study was restricted to southwest Florida because it has been the center of a number of ecological studies (Lugo and Snedaker, 1974; Odum *et al.*, 1982; Twilley *et al.*, 1986), and all four mangrove species and described community types are present, providing the necessary within and between mangrove type samples. Further, human development is limited mostly to the northern and southern extremes, and Rookery Bay is one of the few pristine mangrove estuaries remaining in the world (Saenger *et al.*, 1983).

Data Collection

Between October 1988 and April 1989, a study of the mangrove community characteristics within the Rookery Bay and Ten Thousand Island areas was completed. Twenty-one field sites were chosen that encompassed five mangrove communities defined by Lugo and Snedaker (1974). Nineteen of these 21 sites were occupied for field sampling work.

Field data were collected within a 30.5- by 30.5-m area centered at each sampling site. Included in the data were percent canopy closure and litter and leaf samples from selected sites. In the laboratory, leaf and litter reflectances were obtained. Observations recorded at each site included canopy and understory species type, percent and height, litter type and amount, canopy density, tidal penetration, and color photographs.

In October, near-nadir (<20° zenith angle) canopy light upwelling spectra were collected using a helicopter platform. Location markers, visible from areal and ground surveys, were installed at the 19 sites. Spectral measurements taken from a helicopter platform were centered at the flag markers, as were all measurements describing the canopy characteristics.

Canopy Structure

Canopy Closure

Canopy closure estimates were obtained at each site by using a hand-held hemispherical mirror. Percent canopy closure was estimated as the fraction of mirror area covered by leaves, stems, and/or trunk. At each site, measurements were recorded at 1.5-m intervals along 30.5-m transects in the east-west and the north-south directions. Mean values of the 42 observations taken in the two transects usually differed by <5 percent; however, at sites with very sparse canopies and sites located near abrupt boundaries, transect means could differ by >10 percent. Three replicate measurements of the same transect produced a relative precision error estimate for this methodology of 13.8 percent.

Leaf Area Index (LAI)

An estimate of the mean canopy LAI at each site was generated from the mean canopy closure estimate. This transformation relied on the fact that the canopy's effectiveness in intercepting direct radiation from any incident angle is determined by the fraction of leaf area in the incident direction (Norman, 1979). To generate the function describing this cross-sectional variation with incident direction, three initial assumptions were made. First, the leaf angle distribution was spherical, or all leaf orientations had an equal probability of occurring. Second, the leaves were randomly distributed about the azimuth. This assumption appears to be valid in full cover canopies and even in some canopies where the leaves were not randomly distributed (Norman, 1979). Finally, assuming optically black leaves, the following expression was used to relate the canopy closure measurements to the mean canopy LAI as

$$\mathrm{Ln}(I/I_o) = -k_s VT \quad (1)$$

where I/I_o is the ratio of radiation reaching the ground to incident radiation at the top of the canopy (estimated by 100 percent minus percent canopy closure), VT is the estimated LAI (Leaf density [V] * depth of canopy [T]), and k_s is the spherical extinction coefficient equal to 0.5 (Norman, 1979).

Spectral Measurements

Grey Card Calibration

All reflectance measurements were acquired by using a Spectron Engineering portable radiometer. The radiometer has a 10° field of view and collects spectral information from 368 nm to 1170 nm in 256 channels. It has a nominal spectral resolution of 2.7 nm (Carder and Steward, 1985).

All radiance measurements were made relative to the total local solar and skylight irradiance received by a Kodak 18 percent grey card. The grey card response was corrected for nonspectral uniformity by standardization to a pressed Halon standard. The Halon standard produces about 100 percent response between 400 nm to 2500 nm and is traceable to the National Bureau of Standards (G. A. Carder, Stennis Space Center, personal communication, 1988).

Leaf Spectra

Leaf spectra were taken at the Rookery Bay Marine Laboratory. Leaf samples collected in the field were kept intact as much as possible. Small branches were preferred over single leaves. Field samples were stored in plastic bags and placed on ice immediately. Leaf spectra were acquired within 10 hours after collection. In order to acquire leaf spectra, leaves were stacked (up to 2 or 3 deep) within a grey card area about 25 by 25 cm^2. They were illuminated by using a diffuse light source. Spectra were taken in triplicate, and a grey card reading was taken after each leaf sample was analyzed. Color photographs were taken of each leaf sample. The triplicate spectra acquired of each leaf sample were averaged and normalized to leaf reflectance by using the calibrated grey card upwelling spectra (Figure 3a). Litter and soil reflectances were similarly obtained (Figure 3b).

Canopy Spectra

Recordings of canopy upwelling radiance were made from helicopter platforms at about 57 m above ground level, resulting in a 10- by 10-m ground-projected instantaneous field of view. Calibrated grey card recordings were taken on the ground every 30 to 40 minutes during the radiometer data acquisition.

Normalization of the upwelling data from the sites within the Rookery Bay and Ten Thousand Islands areas required a grey card recording for the time of each site radiance collection. Within about three hours of data collection, 11 grey card recordings at four different times were acquired. A program was written that regressed these observations versus time at each of the 252 wavelengths defining the radiometer's spectral range. The form of the relationship at each wavelength was

$$\mathrm{Ln}(H_{tot}(t)) = a_o + a(t_o - t) \quad (2)$$

where $H_{tot}(t)$ is the total downwelling irradiance (direct plus skylight, in sensor response units); a_o and a are the regression intercept and slope, respectively; and t is the time of the grey card record relative to zero time, t_o. The relationship satisfactorily explained the grey card recording variance with an $R^2 > 0.92$, and most often > 0.94. The exponential form of this expression was used to predict the grey card recording at the time of a particular site data collection.

Radiance upwelling spectra were also taken in triplicate at each site (Figure 4a). Very close correspondence between the triplicate recordings allowed the upwelling radiance spectra to be averaged at each site. One field replicate was acquired in which the same site was occupied at two different altitudes, 57 m and 152 m (Figure 4b). This replicate was used to qualitatively examine the precision of the upwelling radiance recording methodology, spatial scale variation, and atmospheric effects. The replicate spectra showed little discernible differences.

Site and Field Data Description

Generally, species composition within each category followed the Lugo and Snedaker (1974) description. Red mangroves dominated the overwash and fringe forests while black mangroves dominated the interior basin forests, although the latter observation was not as clear as the former. White mangroves were not dominant at any site but were present at all sites, even if only 1 to 5 percent of the total population.

To aid in describing the spectral data and in clarifying subsequent analyses, reflectances at four wavelength bands (US1 [Blue—447 to 453 µm], US2 [Green—553 to 567 µm], US3 [Red—673 to 676 µm], and US4 [NIR—799 to 802 µm]) were generated from the canopy spectra. The range and placement of each band were chosen to best describe the maximum variability in the spectral data and to encapsulate the full range of spectral information. Further, reflectances were generated from the canopy spectra for wavelength bands corresponding to the TM (TM1 [450 to 520 µm], TM2 [520 to 600 µm], TM3 [630 to 690 µm], TM4 [760 to 900 µm]), SPOT Panchromatic (SPP [510 to 730 µm]), and XMS (SP1 [500 to 590 µm], SP2 [610 to 680 µm], SP3 [790 to 890 µm]), and AVHRR (AV1 [580 to 680 µm], AV2 [720 to 1100 µm]) sensors. Note, in the following text, the underlined notations (e.g., US) will refer to reflectances based on bandwidths selected for use in this study and described above, whereas bandwidths and transforms associated with each sensor will be designated by the first two letters of the sensor/satellite name (e.g., TM1 refers to TM sensor band 1).

Table 1 includes a description of the sites and a summary of site descriptors, such as site category, percent species composition and mean highest canopy height, canopy LAI, and a listing of what samples were taken (e.g., canopy or understory leaf, ground litter, or soil). Table 2 lists each variable's number of observations, mean, one standard deviation, and range. Added to the variables already mentioned are normalized difference vegetation index (NDVI) transforms derived from the bandwidths specific to this paper (NDVI_{US}) and TM (TMVI), XMS (SPVI), and AVHRR (AVVI) sensor bandwidths. For each of the above sets of bandwidths, the NDVI transform was calculated as

$$(\mathrm{NIR} - \mathrm{Red})/(\mathrm{NIR} + \mathrm{Red}). \quad (3)$$

Even though problems potentially exist in the use of the NDVI transform (e.g., Baret and Guyot, 1991; Thenkabail *et al.*, 1994), NDVI was selected because it suited the date set, it has been widely used, and it has been shown to be a robust and reliable estimator of vegetation trends and status (e.g., Jensen *et al.*, 1991; Ehrlich *et al.*, 1994).

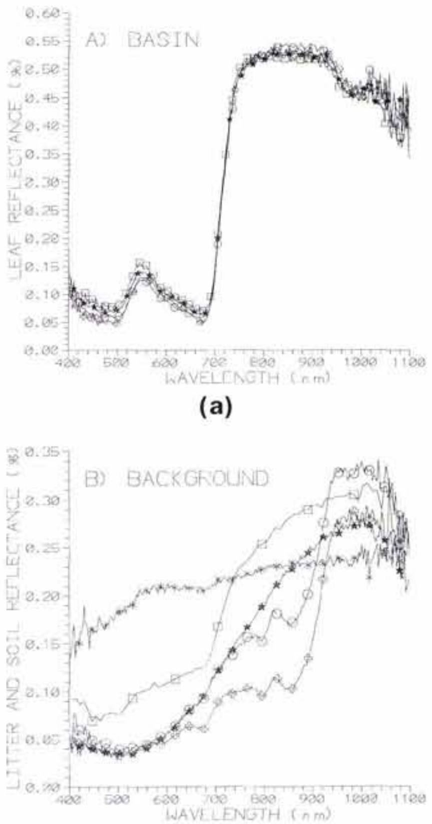

Figure 3. (A) Measured mangrove leaf spectra acquired by using a stacked-plate reflectance design (red canopy [circle], red understory [square], white canopy [star], black canopy [cross]). The basin site contained about 40 percent red (understory — 10 to 12 ft, canopy — 15 to 20 ft), about 30 percent white, and about 30 percent black (canopy — 15 to 20 ft) mangroves. Canopy LAI was estimated to be 2.78. (B) Background spectra of samples obtained at five sites of various mangrove mixture proportions (red mangrove litter [star], mixed red and black [50/50%] mangrove litter [circle], black mangrove [cross], *Spartina alterniflora* [square], and sandy soil [asterisks]).

Site-Specific Leaf and Canopy Reflectance Spectra

Figures 3 and 4 characterize the spectra obtained during the mangrove study in southwest Florida. Figure 3a illustrates the range of leaf spectra found at a site of fairly complex composition, while Figure 3b depicts the range of backgrounds found at five separate sites. Figure 4a shows the range of reflectances calculated from the acquisition of site-specific helicopter radiometer data, and Figure 4b displays two spectra generated from measurements at different altitudes. Figures 5a and 5b display the range of leaf reflectances measured for the black and red mangrove species, respectively.

Simple and Multivariate Correlation Analysis

Site-specific data and the generated canopy reflectance spectra (as described above and in Tables 1 and 2) were compared to uncover any possible indicators of canopy structure and species composition linked to specific spectral bands, band combinations, or band transforms. To reach this goal, a statistical methodology was used that first identified interrelationships between measured canopy variables and second examined the use of single band and multiple bands in explaining the variance in those canopy characteristics.

The statistical analysis was conducted in three steps. First, simple correlations were examined within a correlation matrix with (1) data generated from field measurements and reflectance bandwidths defined in this paper, (2) canopy reflectances associated with satellite sensor bandwidths, and (3) field measurements and canopy reflectances. Second, plots were produced between canopy variables and remote sensing reflectances to inspect the functional form of those correlations. Third, multiple regression analyses were evaluated as predictors of chosen canopy variables. Correlations are reported as the Pearson correlation coefficient (r) and significance as $p>0.05$, unless stated otherwise.

Correlations between Defined Bandwidths and Field Data

Interrelationships were examined within canopy descriptors (e.g., height, LAI, species composition, canopy reflectance) and between canopy descriptors and defined canopy reflectance bands and band transforms (e.g., $NDVI_{US}$) (Table 3). Due to high correlation between the percentage of red, black, and white mangroves, and the minor importance of percent white

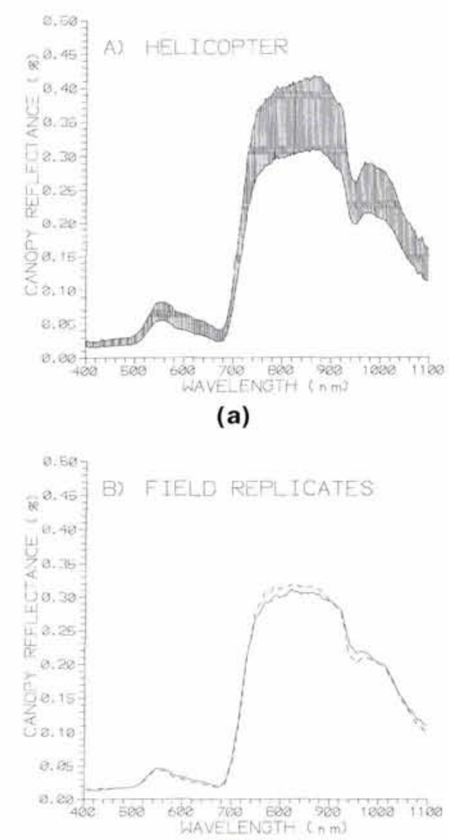

Figure 4. (A) Range of generated reflectance spectra from site-specific upwelling light measurements (mean ± one standard deviation, $N = 23$). (B) Replicate canopy reflectance spectra calculated from radiometer data collected at about 55 m AGL — solid line, and at about 152 m AGL — *dashed line. This site was not occupied but, from the* helicopter, the mangrove mixture was estimated as about 30 percent red and 70 percent black mangrove.

Table 1. Field Site Descriptions

Site[a]	Category[b]	Percent species (red/black/white)	Height (m)	LAI[c] (std)	Samples[d]	Notes
HQ1	BASIN	0/100/ 0	10.5	---	CN/LI	
HQ2	BASIN	50/ 50/ 0	8.5	---	CN/LI	
TH1	BASIN	40/ 30/ 30	6.0	---	---	
HK1	BASIN	20/ 80/ 0	---	---	---	Aerial survey only
GB1	BASIN	35/ 65/ 0	12.2	2.7(0.16)	CN	
DK1	BASIN	18/ 80/ 2	13.7	3.2(0.50)	---	
S1	BASIN	60/ 35/ 5	13.7	3.9(0.19)	---	
ML1	BASIN	30/ 70/ 0	---	---	---	Aerial survey only
CS1	BASIN	30/ 70/ 0	---	---	---	Aerial survey only
HQ4	BASIN[2]	70/ 30/ 0	7.6	---	CN	
AK1	OVERWASH[2]	90/ 5/ 5	6.1	---	CN	
SH1	OVERWASH[2]	90/ 5/ 5	6.1	1.6(0.25)	CN	Lightning strike
S3	OVERWASH[2]	80/ 20/ 0	9.1	3.4(0.52)	---	Peninsula
RM1	OVERWASH	95/ 5/ 0	9.0	---	CN/US	
RM2	OVERWASH	78/ 2/ 20	9.5	---	CN/US/LI	
MQ1	OVERWASH	90/ 5/ 5	7.6	3.5(0.45)	CN	
S2	OVERWASH	90/ 0/ 10	3.4	2.2(0.28)	---	
TH3	FRINGE	100/ 0/ 0	9.6	---	---	
TH2	SCRUB	82/ 18/ 0	2.1(3.1)[f]	---	---	Recovering burn
KI1	SCRUB	0/100/ 0	1.4	0.9(0.12)	CN/SO	Fringe of saltern
KI2	RIVERINE	75/ 25/ 0	9.1	3.6(0.34)	CN	Tidal channel
HQ3	TRANSITION	0/ 4/ 21	5.6	1.8(0.23)	CN/US/LI[e]	

[a]Site names. Because of a mostly open canopy, site TH2 was excluded from the following analysis.
[b]Categories refer to Lugo and Snedaker (1974). OVERWASH[2] notations signify noticeable basin characteristics and BASIN[2] notations signify noticeable overwash characteristics.
[c]Mean estimates of leaf area index were derived from canopy closure site measurements by using $I/I_o = \mathrm{EXP}(-k_s\mathrm{US})$. Leaf area index standard deviations were derived from canopy closure standard deviation estimates.
[d]CN, US, LI, and SO refer to canopy leaf, understory leaf, leaf litter, and soil samples, respectively.
[e]Buttonwood and *Spartina alterniflora* ground cover.
[f]Older black mangroves were sporadically distributed at this site (TH2).

at any site examined, a transform was used to simplify percent species composition comparisons as

$$\text{species percent} = (\text{red\%} - \text{black\%})/(\text{red\%}+\text{black\%}+\text{white\%}). \quad (4)$$

Of the spectral data, only the US2 reflectance band is significantly related to the US4 band reflectance, while all visible bands are significantly correlated (r>0.88) with the US1 and US3 reflectances having the highest correlation (r about 0.97). Species percent is not significantly associated with any included variable, while canopy height is significantly related to the US4 band reflectance (r>0.57), LAI (r>0.77), and NDVI_{US} (r>0.69), but not to any visible band reflectance. Canopy LAI is significantly correlated to US1 and US3 reflectances (r>−0.71) but not US2 or US4 reflectances. Excluding US4 band reflectance and species percent, NDVI_{US} is significantly correlated to all variables (r>−0.63) — the highest correlation is with canopy LAI (r about 0.93).

Scatter plots of NDVI_{US} versus US3 reflectance, NDVI_{US} versus US4 reflectance, and canopy height versus LAI are shown in Figures 6a, 6b, and 6c. Figures 6a and 6b show both the strong relationship between US3 (Red) reflectance and NDVI_{US} and the lack of a monotonic relationship between US4 (NIR) reflectance and NDVI_{US}, respectively. Figure 6c shows the correspondence between canopy height and LAI.

Table 2. Field Variable Univariate Statistics

Variable[a]	OBS#	Mean	STD[b]	Range
Red	20	56%	35%	0% to 100%
Black	20	34%	35%	0% to 100%
White	20	6%	9%	0% to 30%
Height	18	8.3	3.2	1.4 to 13.7
LAI	10	2.7	1.0	0.9 to 3.9
NDVI_{US}	21	0.83	0.04	0.74 to 0.88
TMVI	21	0.80	0.04	0.71 to 0.86
SPVI	21	0.79	0.04	0.70 to 0.85
AVVI	21	0.72	0.04	0.62 to 0.79

[a]Red, black, and white refer to mangrove species types. Height refers to mean canopy height in meters, and LAI to leaf area index estimates. NDVI_{US} refers to the normalized difference vegetation index generated from bandwidths defined in this article, while TMVI, SPVI, and AVVI refer to NDVI transforms derived by using TM, XMS, and AVHRR sensor bandwidths, respectively.
[b]One standard deviation.

Correlation between Satellite Reflectances

All visible band reflectances were significantly and highly correlated (r>0.90, including SPOT panchromatic) with like colors (reflectance bands including NIR) correlating highest (r>0.99) both within and between sensor arrays (Table 4). Blue and red band reflectances were significantly and highly correlated (r>0.97), while correlations between these bands and the NIR bands were not significant except with the AVHRR NIR band (r>0.43). Correlations between NIR and green reflectances were significant but low (r>0.50), while SPOT panchromatic reflectance was significantly correlated (r>0.90) with all visible bands. The highest correlations of these were shown with green reflectance (r>0.99). Significant correlations were found between all vegetation indexes and all visible reflectance bands (r>−0.64, highest with blue and red [r>−0.79]). Finally, all vegetation indexes were highly and significantly correlated (r>0.99).

Correlation between Field Measurements and Satellite Reflectances

Generally, the same colors (reflectances, including NIR) were significantly and highly correlated (r>0.98) (Table 5). The US1 reflectance band was significantly correlated to all visible satellite bands (r>0.87, including the SPOT panchromatic band) and vegetation indexes (r>−0.81), but to no satellite NIR reflectance bands. US2 reflectance was significantly corre-

Table 3. Correlations between Defined Bandwidths and Field Data.

	US1	US2	US3	US4	HT	LAI[1]	$NDVI_{US}$	SPECIES
US1	1.00	0.88 **	0.97 **	0.29 NS	−0.34 NS	−0.71 *	−0.82 **	0.07 NS
US2		1.00	0.92 **	0.55 *	−0.06 NS	−0.21 NS	−0.63 *	0.04 NS
US3			1.00	0.32 NS	−0.35 NS	−0.72 *	−0.84 **	0.02 NS
US4				1.00	0.57 *	0.61 NS	0.23 NS	−0.01 NS
HT					1.00	0.77 *	0.69 *	−0.09 NS
LAI						1.00	0.93 **	0.35 NS
$NDVI_{US}$							1.00	−0.02 NS
SPECIES								1.00

Simple correlations are listed between the canopy LAI and height, canopy reflectances integrated over bandwidths previously defined in this paper along with NDVIs generated by using these band reflectances (Equation 3), and a transform related to the species percent (Equation 4). [1]Leaf area index (LAI) was based on ten observations. All other variable correlations were based on 18 to 21 observations. The simple correlation coefficients are listed with the associated regression significance where ** indicates $p<0.001$, * indicates $p < 0.05$, and NS indicates not significant at the $p < 0.05$ level.

lated to all visible and NIR satellite bands ($r>0.91$ [visible] and $r>0.54$ [NIR]) and vegetation indexes ($r>-0.66$). US3 reflectance closely followed US1 reflectance as highly and significantly correlated to all satellite bands ($r>0.92$) and vegetation indexes ($r>-0.84$), but not with any satellite NIR reflectance band. Conversely, US4 reflectance correlated significantly with the green satellite reflectance bands ($r>0.51$, SP1 and TM2), but not with any satellite vegetation index.

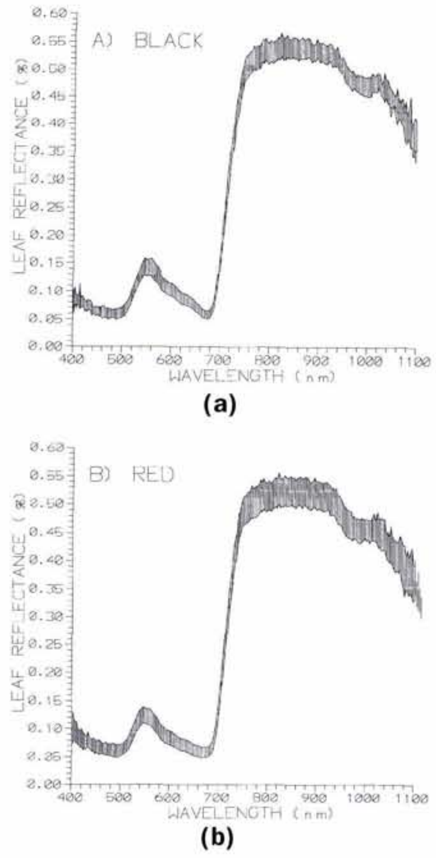

Figure 5. Leaf reflectance spectra acquired of samples taken in the field and transported to the laboratory (stacked-plate). The plots depict the mean ± one standard deviation. (A) black ($N = 8$), (B) red ($N = 13$) mangrove spectra.

Leaf area index was significantly correlated with the SPOT NIR reflectance band (r about 0.63), with the blue and red TM reflectance bands ($r>-0.63$), and with all satellite vegetation indexes ($r>0.90$). Canopy height was significantly correlated to satellite NIR band reflectance ($r>0.54$) and vegetation indexes ($r>0.66$), while percent species composition did not significantly correlate to any satellite reflectance band or vegetation index. The vegetation index ($NDVI_{US}$)—derived from the US3 and US4 bandwidths defined in this report—significantly correlated with all satellite visible bands ($r>-0.66$ [highest with red and blue, $r>-0.77$]) and vegetation indexes ($r>0.97$).

R^2/Cp Analysis

To investigate the relationship between species composition and canopy spectra, an R^2/Cp regression analysis was applied (Hocking, 1976). The analysis calculates R^2 (explained variance) and Cp (model bias estimate) statistics for all combinations of independent variables. Field estimates of species composition (dependent variable) and the reflectance bands and vegetation index generated from the site-specific canopy reflectance spectra (US1, US2, US3, US4, and $NDVI_{US}$—independent variables) were inputs into the analysis. Results of the R^2/Cp analysis showed no simple or multiple linear regression model explained over 4 percent of the species percent variance. Thus, within this data set and choice of reflectance bandwidths, the canopy reflectance was not statistically related to variability in species composition.

Simple Regression Analysis

As a final step in the statistical analysis, canopy LAI was regressed against the vegetation transform, $NDVI_{US}$, derived by using Equation 2 and US3 and US4 reflectances of the site-specific canopy reflectances. The model was significant ($p<0.0001$), with an adjusted R^2 of 0.84 and intercept and slope coefficients of about −19.0 ($p<0.0003$) and about 26.3

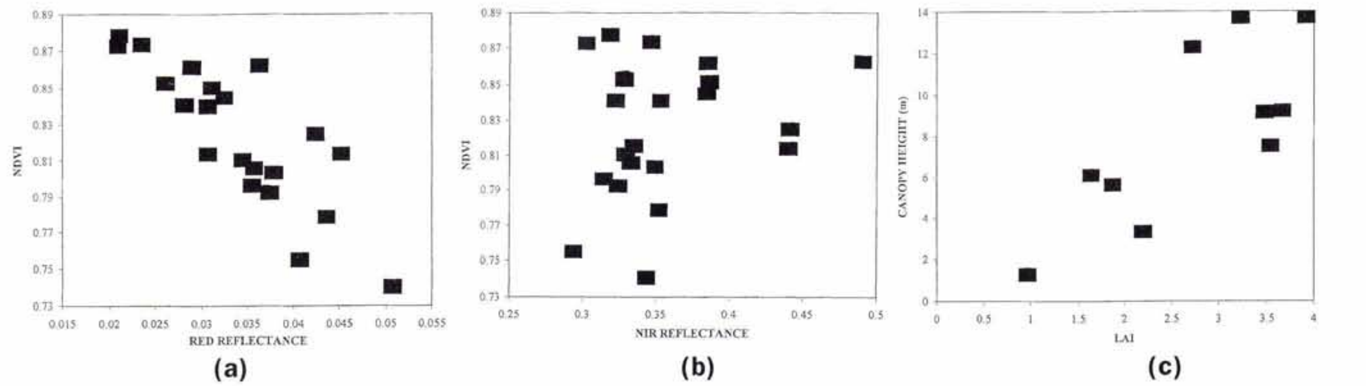

Figure 6. (a) Scatter plots of $NDVI_{US}$ versus Red reflectance. (b) Scatter plots of $NDVI_{US}$ versus NIR reflectance. (c) Scatter plots of canopy height versus LAI.

TABLE 4. CORRELATIONS BETWEEN SATELLITE SENSOR REFLECTANCES.

	AV1	AV2	SPP	SP1	SP2	SP3	TM1	TM2	TM3	TM4	AVNDVI	SPNDVI	TMNDVI
AV1	1.00	0.47 *	0.97 **	0.98 **	1.00 **	0.40 NS	0.96 **	0.98 **	1.00 **	0.40 NS	−0.81 **	−0.80 **	−0.80 **
AV2		1.00	0.66 *	0.57 *	0.45 *	0.99 **	0.38 NS	0.58 *	0.44 *	0.99 **	0.12 NS	0.13 NS	0.13 NS
SPP			1.00	0.99 **	0.96 **	0.59 *	0.91 **	0.99 **	0.95 **	0.59 *	−0.66 *	−0.65 *	−0.65 *
SP1				1.00	0.98 **	0.51 *	0.94 **	1.00 **	0.97 **	0.51 *	−0.73 **	−0.71 **	−0.71 **
SP2					1.00	0.37 NS	0.97 **	0.97 **	1.00 **	0.37 NS	−0.83 **	−0.82 **	−0.82 **
SP3						1.00	0.32 NS	0.52 *	0.36 NS	1.00 **	0.20 NS	0.21 NS	0.22 NS
TM1							1.00	0.93 **	0.97 **	0.32 NS	−0.82 **	−0.82 **	−0.82 **
TM2								1.00	0.96 **	0.52 *	−0.72 **	−0.71 **	−0.70 **
TM3									1.00	0.36 NS	−0.83 **	−0.83 **	−0.83 **
TM4										1.00	0.20 NS	0.21 NS	0.21 NS
AVNDVI											1.00	1.00 **	0.99 **
SPNDVI												1.00	1.00 **
TMNDVI													1.00

Simple correlation coefficients and significance for correlations between canopy reflectances and vegetation indices related to bandwidths defined for TM, XMS and Panchromatic (SPOT), and AVHRR sensors. Significance level as per Table 3. All variable correlations are based on 21 observations.

($p<0.0001$), respectively. A plot of observed canopy LAI versus $NDVI_{US}$ is shown in Figure 7.

Discussion of Results

Canopy and leaf reflectance spectra depict the spectral complexity of the observed mangrove communities. Canopy reflectance variance was high within the fairly diverse mangrove environments (Figure 4). Even in the sparsest sites, however, canopy reflectances were typified by a distinct green peak and NIR plateau with a well-defined red edge. Further, as shown in the scatter plot, the red edge width was narrow, indicating low variance in canopy reflectances between about 700 nm to about 740 nm.

Noteworthy within red and black leaf reflectances is the similar magnitude and the relatively high variability within each species (a variance of about 0.04 to 0.06; Figures 5a and 5b). In a photographic study (Patterson, 1986), it was suggested that, in part, the lower canopy reflectance associated with black versus red mangrove stands resulted from the relatively lower black mangrove leaf reflectance. In fact, black leaf reflectance tended to be somewhat higher than red leaf reflectance; however, the average difference (about 0.02) is less than the scatter about the mean within each species. Additional evidence of this similarity is shown in Figure 3a where leaf reflectances obtained from red, black, and white mangroves at one site were not distinguishable.

The mean and range of LAI values derived within this study were similar to mangrove canopy LAI values reported elsewhere (Odum *et al.*, 1982). Using simple correlation statistics, it was found that LAI variability was not significantly related to species composition although LAI was significantly and positively related to canopy height (r of about 0.77). This result indicates a tendency for canopy depth to increase with canopy height, not remain constant. Eighty-four percent of the LAI variance could be predicted by using any vegetation index examined; however, the linear relationship was not useful at an NDVI lower than about 0.72. Part of this restriction may be related to the selection of sites with fairly

Table 5. Correlations between Field Measurements and Satellite Sensor Reflectances

	AV1	AV2	SPP	SP1	SP2	SP3	TM1	TM2	TM3	TM4	AVNDVI	SPNDVI	TMNDVI
US1	0.94 **	0.35 NS	0.88 **	0.91 **	0.95 **	0.28 NS	1.00 **	0.90 **	0.96 **	0.28 NS	−0.82 **	−0.82 **	−0.82 **
US2	0.97 **	0.61 *	0.99 **	1.00 **	0.96 **	0.55 *	0.91 **	1.00 **	0.95 **	0.55 *	−0.69 **	−0.68 **	−0.67 *
US3	0.98 **	0.40 NS	0.93 **	0.95 **	0.99 **	0.32 NS	0.98 **	0.94 **	1.00 **	0.32 NS	−0.84 **	−0.85 **	−0.85 **
US4	0.41 NS	0.99 **	0.59 *	0.52 *	0.38 NS	1.00 **	0.33 NS	0.52 *	0.36 NS	1.00 **	0.19 NS	0.21 NS	0.21 NS
HT	−0.25 NS	0.55 *	−0.04 NS	−0.11 NS	−0.29 NS	0.58 *	−0.30 NS	−0.10 NS	−0.30 NS	0.58 *	0.66 *	0.67 *	0.68 *
LAI	−0.55 NS	0.61 NS	−0.17 NS	−0.31 NS	−0.61 NS	0.63 *	−0.69 *	−0.29 NS	−0.64 *	0.63 NS	0.90 **	0.91 **	0.91 **
$NDVI_{US}$	−0.78 **	0.15 NS	−0.62 *	−0.68 **	−0.80 **	0.23 NS	−0.81 **	−0.66 **	−0.81 **	0.23 NS	0.98 **	0.99 **	1.00 **
SPECIES	0.00 NS	0.03 NS	0.05 NS	0.03 NS	0.00 NS	0.02 NS	0.02 NS	0.03 NS	0.01 NS	0.01 NS	0.00 NS	0.01 NS	0.00 NS

Simple correlations are listed between canopy LAI height, percent species composition, band reflectance, and NDVIs generated by using bandwidths defined in this paper and band reflectances and vegetation indices generated from satellite sensor bandwidths. Variable definitions, significance level, and number of observations as per *Table 3* and *Table 4*.

full canopies or to the very effective light interception by the mangrove canopy (Odum *et al.*, 1982).

Correlation results imply that no decisive differences existed between the reflectance bands specifically chosen to match the set of canopy reflectance spectra and the reflectance bands associated with each of the three satellite sensors. Within the full set of reflectance bands, excluding reflectance bands describing the same colors, blue and red reflectances were more highly correlated than any other band combination while, except for the AVHRR NIR reflectance, only green reflectance correlated significantly with any NIR reflectance. SPOT panchromatic reflectance was highly correlated with all visible reflectances, especially with green reflectance, and NDVI variance was dominated by red reflectance variability. In general, blue and red reflectances were redundant, as were SPOT panchromatic and green reflectances and all NDVIs generated from the various sets of reflectance bands. Additionally, species composition was not related to any field variable measured or derived, or to any single or multiple linear combination of reflectance bands and vegetation index.

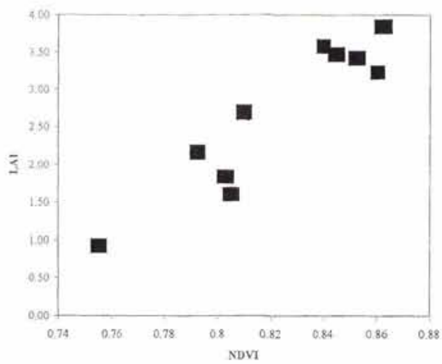

Figure 7. A plot of canopy LAI versus $NDVI_{US}$. The regression model explained 84 percent of the canopy LAI variance and had intercept and slope coefficients of about −19.0 and about 26.3, respectively. LAI was generated from field measurements of *canopy closure* (Equation 1).

Conclusions

Results of this study showed the complexity and difficulties in describing the spectral and structural aspects of mangroves. Differences between mean leaf reflectances associated with black and red mangroves were less than variability within each species, suggesting difficult segregation of mangrove communities by using leaf optical properties alone. Canopy LAI was significantly and positively related to canopy height, and 84 percent of the LAI variance was explained by using a normalized difference vegetation index. Species composition was not related to canopy LAI or to any combination of reflectance bands and vegetation indexes. Reflectances and vegetation indexes were generated from the canopy spectra by using either user-defined bandwidths or bandwidths defined for the AVHRR, TM, and SPOT panchromatic and XMS sensors. Correlation analysis of this set suggested that blue and red reflectances were redundant as were SPOT panchromatic and green reflectances and all generated normalized difference vegetation indexes. Spectrally, no simulated sensor bands or sensor band transform exhibited clearly noticeable differences in defining canopy LAI.

These results are limited by the number and type of sites sampled, the techniques used, and the region of analysis; however, they should provide a guide when attempting mangrove mapping by using remote sensing. A fairly good estimate of leaf area index should be expected by using a simple transform of the red and NIR band reflectances available from a number of satellite or aircraft sensor systems. Similarity of the black and red leaf reflectance spectra and the lack of covariation between species composition and LAI or any reflectance band or remote sensing vegetation index suggest species composition may not be as easily estimated from remote sensing imagery. Canopy height was somewhat correlated to canopy NIR reflectance, but this may depend more on its correlation to LAI than on a direct relationship to canopy reflectance. Future work will use new instruments to define leaf spectral properties (instead of the stacked leaf method) and more directly measure light attenuation through the canopy in order to decrease the possibility of error in estimating leaf area index. Further, the use of other vegetation indexes may improve the ability to describe canopy characteristics (e.g., Baret and Guyot, 1991; Price, 1993; Thenkabail *et al.*, 1994). Finally, a better understanding is needed of the direct relationship between incident light, canopy structure, leaf optical characteristics, and the light detected at the sensor. Another paper examines the use of a light-canopy interaction model to uncover these relationships (Ramsey and Jensen, 1995).

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(Received 6 June 1994; accepted 11 October 1994; revised 22 December 1994)